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COMBUSTION STABILITY OF A HYDROGEN FUEL JET ISSUING NORMAL TO AN AIRSTREAM

By John W. Sheldon, Gilbert B. Chapman, II, and Paul D. Reader

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Cleveland, Ohio

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COMBUSTION STABILITY OF A HYDROGEN FUEL JET ISSUING NORMAL TO AN AIRSTREAM*

By John W. Sheldon, Gilbert B. Chapman, II
and Paul D. Reader

SUMMARY

The limiting values of the geometric and local flow variables are determined for stable combustion of an unobstructed hydrogen fuel jet issuing normal to an airstream. An extensive map of blowout conditions at pressures between 0.4 to 1.0 atmosphere is presented. A range of blowout velocity from 10 to 210 feet per second was covered. The data for a single fuel jet are correlated by parameters similar to those used for flame stabilization on a cylindrical flameholder. The stabilizing effect of closely spaced adjacent fuel orifices is illustrated by data for two jets spaced 3 and 6 diameters apart.

INTRODUCTION

Theoretical advantages of using hydrogen fuel in a high altitude, high flight Mach number ramjet engine are shown in reference 1. These advantages are a result of the high reactivity and cooling capacity of hydrogen.

For inlet air pressure above 1 atmosphere and inlet air velocity below 300 feet per second, efficient ramjet combustors utilizing hydrogen fuel have been developed, which do not require flameholders, but seat the flame at each fuel injection orifice on a spray bar (refs. 2 and 3). This configuration is inefficient and unstable at more severe inlet conditions (ref. 4).

The program reported herein was designed to determine the limiting values of the geometric and local flow variables for stable combustion of an unobstructed hydrogen jet. An attempt was made to correlate the data for single hydrogen jets by a combination of flame blowout parameters given in reference 5.

* Title, Unclassified

A 3- by 5-inch cross-section combustor was used in the tests. Single and multiple fuel injection orifices were drilled normal to the wall. A range of orifice diameters from 0.028 to 0.104 inch was covered. The stabilizing effect due to the interaction of adjacent jets was investigated by varying the orifice spacing. Blowout pressure was determined for airflows of 1.0 to 10.0 pounds per second per square foot of combustor cross section and fuel flows per orifice of 0.4 to 4.4 pounds per hour. All tests were conducted with air and fuel at approximately room temperature.

SYMBOLS

D	diameter
P	pressure
Re	Reynolds number
T	temperature
V	velocity
x,y,z	constant exponents on D, P, and T, respectively
μ	viscosity
ρ	density
φ	equivalence ratio

Subscripts:

a	air
j	pertaining to the fuel jet at the injection orifice

APPARATUS

The test facility is diagrammed schematically in figure 1. Air was supplied by the laboratory air system at a pressure of approximately 40 pounds per square inch. The air flowed through an ASME standard metering orifice and was then regulated by remotely controlled butterfly valves. From the control valves air flowed through the test section and into the laboratory altitude exhaust system. The pressure level in the test section was controlled by butterfly valves between the test section and the altitude exhaust header.

A sketch of the rectangular test section is shown in figure 2. The airflow entering the test section accelerated over the 1-inch-thick block attached to the top wall, which minimized the boundary layer at the point of fuel injection. The fuel flowed through a sonic flow-metering orifice and was then injected downward from an injection orifice flush with the block. Ignition was accomplished with a retractable spark electrode.

Combustor static pressure was measured by a wall tap in the same cross-sectional plane as the fuel injection orifice. The pressure tap was connected to a pressure transducer and the transducer output was indicated on an automatic balancing x-y potentiometer.

PROCEDURE

Data Recording Procedure

Before a blowout data point was taken, predetermined values of fuel and airflow rates were set. Combustor pressure was set at a sufficiently high value to establish a stable flame and the spark electrode was withdrawn. Then the combustor pressure was slowly reduced. The flame was observed through a window in the test section and when blowout occurred a manually applied input to the x-y recorder identified the value corresponding to combustor pressure at blowout.

For the multiple orifice configurations, blowout was considered to occur when both jets were out.

Test Conditions

Blowout pressure was determined for the following flow conditions:

Airflow per square foot of combustor cross section, lb/(sec)(sq ft)	1.0 to 10.0
Inlet air velocity, ft/sec	10 to 210
Fuel flow per injection orifice, lb/hr	0.4 to 4.4
Combustor pressure, atm	0.4 to 1.0

Inlet Air Velocity Profile

A velocity survey was made in the cross-sectional plane of fuel injection. A four-tube total-pressure rake was used to measure total pressure at eight vertical positions in the duct. These pressures were indicated on a micromanometer and recorded for two typical combustor-inlet conditions. From these total pressures, the static pressure, and the air temperature, the velocity profiles were computed. These profiles were comparatively flat, varying less than ±8 percent from the average value (fig. 3).

RESULTS

The combustion stability data are tabulated in table I. Sketches of the three general types of single jet flames are shown in figure 4. The data are plotted in terms of blowout pressure, the dependent variable, against fuel flow for various values of airflow (figs. 5 to 8). For a given airflow the plotted curve represents the minimum pressure for combustion, that is, blowout. Unstable combustion was frequently observed when the operating pressure was within about 0.5 inch of mercury of the minimum value. The approximate conditions under which each general type of flame was observed is indicated in figure 5.

Effect of Flow Parameters

Both air- and fuel-flow rates have a strong influence on blowout pressure for a single fuel injection orifice (fig. 5). At constant fuel flow an increase in airflow raised the blowout pressure, but slowly enough so that the air velocity also increased. At constant airflow a minimum blowout pressure occurred at a comparatively low (subsonic) fuel flow. Blowout pressure was reduced at the highest fuel-air ratios; however, at this condition the fuel jet penetrated across the combustor and blowout pressure was more likely to be dependent on the duct geometry than on the orifice geometry.

Effect of Geometric Parameters

The effect of fuel injection orifice diameter is illustrated in figure 6. The actual data points are omitted for clarity; only the faired data curves from figure 5 are shown. As might be expected, the blowout pressure is reduced at constant fuel flow by an increase in injection orifice diameter. For example, at an airflow of approximately 2.75 pounds per second per square foot the maximum blowout pressure obtained with the 0.104-inch-diameter orifice was 19.3 inches of mercury, while the maximum blowout pressure obtained with the 0.052-inch-diameter orifice was 24.3 inches of mercury. Data presented in reference 6 for a narrow range of flow conditions support these single-jet data.

Blowout data for two orifices spaced 3 diameters apart are presented for two orifice diameters in figure 7. As flame blowout was approached (by lowering burner pressure) with the double-orifice configurations, the two jets would alternately blow out and relight. Blowout was recorded when both jets were out. At the high fuel flows, airflow has little effect on blowout pressure. Blowout pressure for the configuration (with 0.052-in.-diam. orifices) was between 20.6 and 24.2 inches of mercury for airflows from 2.4 up to 6.6 pounds per second per square foot at fuel flows above 1.0 pound per hour per orifice. The data for two orifices spaced 6 diameters apart (fig. 8) approach the values obtained for a single orifice.

The faired data curves for an orifice diameter of 0.052 inch are replotted in figure 9(a) to show the effect of orifice spacing. At a spacing of 3 diameters there is a stabilizing effect of the adjacent orifice producing an average reduction in blowout pressure of about 5 inches of mercury below the single-jet blowout pressure. The slightly poorer performance of the two-jet 6-diameter spacing may have been due to the flow disturbances accompanying intermittent blowout and reignition of a jet.

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A similar plot for the 0.081-inch-diameter orifice gives an average blowout pressure reduction that was approximately 7 inches of mercury with the 3-diameter spacing (fig. 9(b)). The stability of the 6-diameter spacing approximated an average between the single jet and the 3-diameter spacing.

DISCUSSION

Correlation Parameters

The combustion stability of a normal injected fuel jet apparently depends upon the flameholding action of the jet. The jet offers an obstruction to the airflow and the flame seats in the resulting recirculation zone. This flameholding action may be similar to the flameholding properties of a cylinder in the cross flow of a premixed fuel-air mixture. For the case of a cylindrical flameholder, reference 5 gives the following relation between the flow variables at blowout:

$$\frac{V_a}{D^x P_a^y T^z} = f(\varphi)$$

where x, y, and z are empirical exponents, all positive in sign. The values of x and y were determined by trial and error to be 0.5 and 1.0, respectively. Since the fuel jet spreads as it flows out of the injection orifice it is difficult to determine the correctly weighted diameter to use in the stability relation. The injection orifice diameter D_j was decided upon with the intention that the value of x could correct for the discrepancy between D_j and the hypothetical flameholder diameter.

The temperature term was dropped from the stability relation since this investigation was carried out at essentially constant inlet fuel and air temperature conditions.

The effect of fuel flow on stability was correlated by the use of fuel Reynolds number. The fuel Reynolds number was one of many parameters inspected; its use was prompted by the correlation of jet penetration (ref. 7). The fuel-flow rate was a comparatively insensitive parameter, especially at the low air velocities and consequently the correlation with fuel Reynolds number should not be taken to imply a particular blowout mechanism.

The effect of equivalence ratio was assumed to be most directly dependent upon a fuel Reynolds number defined as

$$Re_j = \frac{V_j D_j \rho_j}{\mu}$$

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The stability relation could then be plotted as $P_a\sqrt{D_j}$ against V_a for curves of constant Re_j (fig. 10). While this simplified picture of jet stability is helpful in correlating single jet blowout, it is entirely inadequate when multiple-jet interaction occurs.

Spray Bar Combustor Design

The combustion stability data for the individual hydrogen jets may be used to predict the stability limits of a hydrogen combustor employing normal injecting spray bars. Calculations based on the method of reference 7, as well as observations made during this investigation, indicate that for practical fuel-flow rates the fuel will penetrate well past the spray bar boundary layer, avoiding the recirculation zone completely. At this condition the fuel jet should have stability characteristics similar to the wall jet.

The interaction of one fuel jet with another or with combustor hardware will probably have a favorable effect on combustion stability. Increased stability may result not only from reduced local air velocity, but also from the availability of ignition sources, for example, a jet may blow out but be relit by nearby jet and hot hardware. Hence, the application of data reported herein to a spray bar combustor should give a conservative estimate of combustor stability.

Wall Jet Combustor

The extensive map of combustion stability of a hydrogen jet presented herein may be applied to the design of a combustor injecting fuel from the wall. If this were done, the combustor-inlet conditions must be less severe than those encountered in most ramjets. The possible advantages of such a combustor are a low pressure loss and simplicity.

Data obtained indicate that a wall jet combustor with inlet temperature of 80° F would be restricted to an inlet air velocity below 200 feet per second at a combustor pressure of 25 to 30 inches of mercury.

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CONCLUSIONS

The following conclusions were reached concerning the combustion stability of a hydrogen fuel jet:

1. Maximum stability for a fuel jet occurs at a low (subsonic) fuel injection velocity.

2. The parameter $P_a\sqrt{D_j}$, previously used to describe blowout of a premixed fuel-air mixture from a cylindrical flameholder, was moderately effective in correlating the jet blowout data. (Where P_a is the air pressure and D_j is the diameter of the fuel jet at the injection orifice.)

3. Large injection orifices produce more stable flames than small injection orifices for particular values of the combustor flow parameters.

4. A stabilizing effect was obtained from the presence of adjacent fuel jets, but the effect diminished rapidly with increased distance between orifices.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, May 1, 1959

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TABLE I. - COMBUSTION STABILITY DATA FOR HYDROGEN FUEL JET

(a) Number of orifices, 1

Orifice diameter, in.	Airflow rate, lb/(sec)(sq ft)	Fuel-flow rate, lb/hr	Combustor static pressure, in. Hg abs	Velocity, ft/sec
0.0280	0.790	0.208	25.3	12.8
	.778	.168	22.8	13.9
	.778	.215	25.0	12.7
	.780	.252	27.0	11.8
	.778	.296	28.4	11.2
	.775	.391	26.4	12.0
	.769	.373	26.1	12.0
	.769	.438	28.6	11.0
	.759	.474	30.0	10.3
	.749	.516	29.8	10.3
	1.41	.155	23.3	24.7
	1.43	.232	24.5	23.8
		.250	25.9	22.5
		.286	26.6	21.9
		.334	28.1	20.7
	1.43	.385	28.7	20.2
		.424	29.4	19.8
		.472	30.4	19.1
		.516	29.0	20.0
	1.03	.148	22.5	18.5
	1.03	.199	25.5	16.2
	1.02	.241	26.9	15.4
	1.02	.282	27.8	14.9
	.976	.341	29.7	13.3
	.976	.394	30.4	13.0
.0520	2.87	.680	23.7	50.3
	2.86	.875	24.4	48.8
		1.04	24.3	49.1
		1.19	24.0	49.6
		1.33	23.9	49.9
	2.86	1.47	24.0	49.6
	2.86	1.63	23.6	50.6
	2.93	1.77	24.6	49.7
	2.94	1.92	23.9	51.4
	2.93	2.08	23.4	52.1

TABLE I. - Continued. COMBUSTION STABILITY DATA FOR HYDROGEN FUEL JET

(a) Continued. Number of orifices, 1

Orifice diameter, in.	Airflow rate, lb/(sec)(sq ft)	Fuel-flow rate, lb/hr	Combustor static pressure, in. Hg abs	Velocity, ft/sec
0.0520	3.69	0.722	27.0	56.9
	3.73	.869	26.7	58.3
	3.69	1.04	26.6	57.5
	3.70	1.18	26.9	57.4
	3.73	1.33	26.9	57.8
	3.73	1.48	27.2	57.2
		1.63	27.1	57.5
		1.77	26.9	57.8
		1.92	26.4	59.0
		2.08	26.4	58.9
	1.65	.725	19.1	36.3
		.892	19.7	35.2
		1.03	19.8	35.0
		1.19	19.2	36.1
	1.59	1.34	19.2	34.8
		1.49	20.1	33.2
		1.63	19.3	34.6
		1.78	18.9	35.4
		1.93	18.5	36.1
		2.09	18.0	37.1
	1.62	.280	18.7	36.6
	1.65	.337	17.9	39.0
		.398	18.2	38.4
		.455	19.2	36.4
		.210	17.8	39.2
	1.65	.511	18.8	37.2
		.577	18.9	36.9
		.635	18.8	37.1
		.693	18.9	36.9
		.755	19.1	36.6
	1.65	.830	19.2	36.4
	2.80	.204	19.2	61.4
		.270	22.3	52.9
		.331	22.4	52.7
		.390	22.7	52.0

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TABLE I. - Continued. COMBUSTION STABILITY DATA FOR HYDROGEN FUEL JET

(a) Continued. Number of orifices, 1

Orifice diameter, in.	Airflow rate, lb/(sec)(sq ft)	Fuel-flow rate, lb/hr	Combustor static pressure, in. Hg abs	Velocity, ft/sec
0.0520	2.80	0.453	22.8	51.7
↓	↓	.513	22.7	52.0
		.562	24.8	47.6
		.563	23.6	50.0
		.558	22.9	51.5
	2.80	.563	23.3	50.6
	↓	.629	23.5	50.2
		.689	23.2	50.9
	2.78	.737	23.8	49.2
	2.78	.824	23.3	50.3
	3.77	.269	24.9	63.1
	↓	.209	22.8	68.9
		.334	25.5	61.8
		.393	25.9	60.8
		.451	26.4	59.5
	3.77	.512	26.7	58.9
	3.78	.577	26.8	58.7
	↓	.638	26.8	58.7
		.706	26.5	59.3
		.759	26.5	59.4
	3.78	.828	26.0	60.4
	1.20	.216	15.7	32.3
	↓	.280	15.6	32.5
		.342	15.8	32.1
		.401	16.4	30.9
	1.20	.518	16.5	30.7
	↓	.580	16.7	30.4
		.642	17.1	29.7
		.699	17.2	29.5
		.759	16.9	30.0
	1.20	.821	17.3	29.3
	↓	.573	16.0	31.7
		.725	16.6	30.6
		.882	17.2	29.5
↓	↓	1.03	17.5	29.0

TABLE I. - Continued. COMBUSTION STABILITY DATA FOR HYDROGEN FUEL JET

(a) Continued. Number of orifices, 1

Orifice diameter, in.	Airflow rate, lb/(sec)(sq ft)	Fuel-flow rate, lb/hr	Combustor static pressure, in. Hg abs	Velocity, ft/sec
0.0520	1.20	1.16	17.7	28.6
		1.32	17.9	28.3
		1.47	17.4	29.2
.0810	3.38	.772	21.3	65.5
		1.08	23.7	58.7
		1.39	24.3	57.3
		1.71	25.2	55.2
		2.03	24.9	55.9
		2.20	24.3	57.3
		1.61	23.3	59.6
		2.15	24.5	56.7
		2.75	23.4	59.4
		2.74	23.3	59.6
		3.38	22.4	62.1
	4.66	1.56	24.8	77.5
	4.66	2.12	27.7	69.4
		2.73	28.6	67.2
	4.63	3.36	27.4	69.6
	4.65	3.95	26.6	71.9
	4.68	.767	22.7	84.5
	4.67	1.07	25.0	76.5
		1.39	26.2	72.9
		1.71	27.2	70.3
		2.03	27.3	70.0
		2.19	25.9	73.8
	6.35	.914	26.3	98.4
	6.32	1.38	28.1	91.8
		1.82	29.2	88.3
		2.09	29.8	86.6
	2.47	.767	19.8	52.6
	2.51	1.10	20.6	51.5
	2.52	1.40	21.6	49.0
	2.48	1.73	21.7	47.9
		2.05	20.5	50.6
		2.34	20.2	51.3

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TABLE I. - Continued. COMBUSTION STABILITY DATA FOR HYDROGEN FUEL JET

(a) Continued. Number of orifices, 1

Orifice diameter, in.	Airflow rate, lb/(sec)(sq ft)	Fuel-flow rate, lb/hr	Combustor static pressure, in. Hg abs	Velocity, ft/sec
0.0810	2.54	0.658	19.6	53.6
		.817	20.5	51.2
		.392	17.5	59.9
	3.48	.388	20.2	70.7
	3.40	.554	20.0	69.6
	3.38	.729	21.7	63.8
	3.42	.833	21.9	63.9
	4.68	.404	26.7	71.5
	4.90	.536	23.9	82.9
	4.68	.778	23.6	80.5
	6.57	.773	25.8	103.0
	6.56	.549	30.5	86.8
.1040	5.06	.684	21.3	99.3
	5.06	.772	19.3	109.2
	5.04	.864	18.3	114.7
	5.04	.986	18.3	114.7
	5.04	1.12	18.8	111.7
	5.06	.797	20.7	102.0
		1.36	20.1	104.9
		1.67	21.1	100.0
	5.06	.754	20.2	104.4
	5.06	.880	18.5	114.2
	5.04	1.53	20.8	101.0
	5.06	1.83	21.7	97.2
	5.04	1.98	22.6	93.0
	5.04	2.13	22.7	92.7
	5.04	2.25	22.9	91.9
	5.06	1.22	19.5	108.4
		.699	22.4	94.2
		.919	18.8	112.1
	6.55	1.05	19.8	138.2
		1.07	20.7	132.8
		1.17	20.0	137.2
		1.29	20.1	136.9
		1.40	20.9	131.6

TABLE I. - Continued. COMBUSTION STABILITY DATA FOR HYDROGEN FUEL JET

(a) Continued. Number of orifices, 1

Orifice diameter, in.	Airflow rate, lb/(sec)(sq ft)	Fuel-flow rate, lb/hr	Combustor static pressure, in. Hg abs	Velocity, ft/sec
0.1040	6.55	1.54	21.2	129.5
↓	↓	1.65	21.6	127.3
		1.77	22.1	124.3
		1.89	22.5	122.2
		2.02	23.2	118.5
	6.55	2.14	23.2	118.3
	6.55	2.25	23.6	116.3
	6.56	.911	22.2	123.5
	6.56	.796	25.0	109.9
	8.19	1.49	23.0	148.6
	8.19	1.72	22.7	150.9
	8.19	1.95	22.9	149.5
	7.99	2.25	24.3	137.3
	7.99	1.12	23.0	145.4
	3.05	1.84	19.0	67.5
	3.03	2.16	19.5	65.4
	3.04	2.46	19.4	65.9
	3.03	2.78	19.5	65.4
	3.04	3.09	19.8	64.6
	3.06	3.41	19.7	65.2
	3.05	3.72	19.8	64.5
	3.04	4.03	19.2	66.3
	3.04	4.40	18.9	67.4
	6.66	1.84	21.9	127.6
	6.68	2.16	22.9	121.9
	6.71	2.48	23.3	120.2
	6.68	2.78	24.6	113.3
	6.71	3.12	24.9	112.6
	↓	3.42	26.3	106.6
		3.72	26.7	105.0
	6.71	4.04	27.6	101.6
	6.67	4.41	28.6	97.5
	3.02	1.89	19.9	64.0
	↓	2.45	19.6	65.0
↓		3.09	19.6	65.0

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TABLE I. - Continued. COMBUSTION STABILITY DATA FOR HYDROGEN FUEL JET

(a) Continued. Number of orifices, 1

Orifice diameter, in.	Airflow rate, lb/(sec)(sq ft)	Fuel-flow rate, lb/hr	Combustor static pressure, in. Hg abs	Velocity, ft/sec
0.1040	3.02	3.72	19.8	64.4
		4.32	18.8	67.6
	2.96	.763	16.2	77.3
		1.04	17.4	72.0
		1.35	18.1	69.2
	2.96	1.75	19.3	64.9
	2.08	.795	15.1	58.5
		1.09	16.4	53.9
		1.43	16.9	52.4
		1.71	17.1	51.8
	2.08	.982	15.9	55.8
		1.22	16.5	53.6
		1.56	17.0	52.0
		.704	15.3	57.8
		1.83	16.8	52.6
	2.08	1.97	16.3	54.4
		2.25	16.7	53.1
	1.28	.748	13.9	39.1
		.718	13.7	39.7
		1.05	13.7	39.7
	1.28	1.19	13.8	39.4
	5.07	1.59	21.2	99.5
	5.06	2.14	24.2	87.0
	5.07	2.79	27.4	77.2
	5.05	4.05	27.3	77.1
	6.59	2.00	23.8	115.1
	6.59	3.51	29.8	91.9
	3.01	1.65	20.4	61.6
	3.01	3.30	20.4	61.5
	3.00	.886	17.2	72.5
	3.00	1.88	21.0	59.4
	2.22	.792	15.9	58.3
	2.22	1.31	18.7	49.3
	2.22	2.02	19.4	47.7
	5.04	2.02	23.8	88.2

TABLE I. - Continued. COMBUSTION STABILITY DATA FOR HYDROGEN FUEL JET

(a) Concluded. Number of orifices, 1

Orifice diameter, in.	Airflow rate, lb/(sec)(sq ft)	Fuel-flow rate, lb/hr	Combustor static pressure, in. Hg abs	Velocity, ft/sec
0.1040	5.05	1.49	21.8	96.6
↓	5.03	.847	23.5	89.0
	6.52	1.03	26.7	101.4
	6.54	1.47	23.8	114.1
	6.53	2.07	25.1	108.0
	8.14	2.09	27.7	122.2
	8.16	1.52	27.4	124.0

(b) Number of orifices, 2; orifice spacing, 3 orifice diameters

Orifice diameter, in.	Airflow rate, lb/(sec)(sq ft)	Fuel-flow rate, lb/hr	Combustor static pressure, in. Hg abs	Velocity, ft/sec
0.0520	3.51	0.751	18.3	79.9
↓	3.51	.935	20.5	71.3
	3.50	1.08	21.8	66.9
	↓	1.32	23.8	61.3
		1.62	22.4	65.1
	3.50	1.94	24.2	60.3
	5.43	.736	19.9	113.6
	5.57	1.20	22.7	101.3
	5.54	1.35	24.2	94.5
	5.57	1.51	22.8	100.8
	5.57	1.66	22.4	102.7
	5.56	1.83	23.5	97.7
	5.57	1.95	23.4	98.3
	5.57	2.08	23.4	98.3
	6.58	.755	24.2	112.2
	6.68	.899	20.7	133.0
	6.71	.737	22.2	124.5
	6.69	1.04	22.4	123.1
	6.70	1.24	21.7	127.2
	6.70	1.44	21.3	129.5
	6.69	1.60	21.4	128.8
	6.63	1.79	21.3	128.3
	6.63	1.92	20.9	130.5
	2.45	.756	18.2	55.5
	2.43	.956	20.7	48.5

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TABLE I. - Continued. COMBUSTION STABILITY DATA FOR HYDROGEN FUEL JET

(b) Continued. Number of orifices, 2; orifice spacing, 3 orifice diameters

Orifice diameter, in.	Airflow rate, lb/(sec)(sq ft)	Fuel-flow rate, lb/hr	Combustor static pressure, in. Hg abs	Velocity, ft/sec
0.0520	2.42	1.26	21.7	46.4
		1.45	21.3	47.3
		1.68	21.2	47.6
		1.93	20.6	48.9
		.374	16.8	60.0
	2.44	.512	19.4	52.3
	2.44	.651	20.9	48.6
	2.42	.815	21.5	47.0
	2.42	1.00	21.1	47.7
	6.48	.431	24.2	111.0
	6.49	.556	21.9	123.1
	6.50	.860	25.2	106.9
	5.42	.381	20.5	109.7
		.523	19.1	117.7
		.677	19.5	115.3
	5.42	.808	21.8	103.1
		.910	23.6	95.3
		1.02	22.5	100.0
	3.51	.383	15.8	92.1
		.548	18.2	79.9
	3.51	.733	21.8	66.8
		.912	22.7	64.2
	3.49	1.05	23.1	62.6
		.151	20.2	71.7
		.234	17.2	84.2
	3.49	.330	15.6	92.9
		.392	17.2	84.2
	2.38	.146	14.3	69.8
		.156	13.6	73.1
		.229	13.4	74.2
	2.38	.269	14.2	70.0
		.306	14.4	69.0
		.344	15.3	65.0
		.384	15.8	62.9
		.403	16.4	60.6

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TABLE I. - Continued. COMBUSTION STABILITY DATA FOR HYDROGEN FUEL JET

(b) Continued. Number of orifices, 2; orifice spacing, 3 orifice diameters

Orifice diameter, in.	Airflow rate, lb/(sec)(sq ft)	Fuel-flow rate, lb/hr	Combustor static pressure, in. Hg abs	Velocity, ft/sec
0.0520	5.32	0.146	26.5	83.6
↓	5.32	.182	26.9	82.4
	5.29	.286	23.5	94.0
	↓	.326	21.1	104.4
		.382	19.4	113.5
	5.29	.409	18.8	117.1
	6.45	.253	29.7	90.1
	6.41	.301	28.8	92.5
	↓	.330	28.1	94.7
		.375	24.8	107.3
↓	6.41	.409	22.7	117.2
.0810	4.68	.793	17.2	111.4
↓	4.69	1.14	15.7	122.2
	4.70	1.49	16.5	116.8
	4.70	1.86	17.7	108.9
	4.70	2.16	19.9	96.3
	6.30	.751	26.8	96.2
	↓	1.04	18.9	136.5
		1.34	17.5	147.0
		1.74	17.8	145.0
	6.31	2.03	19.7	130.8
	6.31	2.25	20.0	128.8
	9.44	1.05	28.6	134.5
	9.47	1.36	23.8	162.6
	9.45	1.70	21.4	180.6
	9.44	2.19	20.5	188.0
	3.40	.803	13.3	104.9
	↓	1.11	14.5	96.1
		1.43	16.8	83.3
		1.78	17.8	78.4
	3.40	2.25	19.0	73.5
	↓	.379	18.2	76.7
		.576	14.5	96.1
		.744	13.1	106.5
↓	↓	.946	13.2	105.7

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TABLE I. - Continued. COMBUSTION STABILITY DATA FOR HYDROGEN FUEL JET

(b) Concluded. Number of orifices, 2; orifice spacing, 3 orifice diameters

Orifice diameter, in.	Airflow rate, lb/(sec)(sq ft)	Fuel-flow rate, lb/hr	Combustor static pressure, in. Hg abs	Velocity, ft/sec
0.0810	3.40	1.12	14.5	96.4
	4.67	.391	22.5	85.3
	4.68	.576	19.2	100.2
	4.67	.793	16.2	118.8
	4.68	.952	15.3	125.7
	4.68	1.12	15.5	124.5
	6.20	.454	26.1	97.6
	6.21	.620	24.8	103.0
	6.26	.816	20.4	126.1
	6.25	1.10	19.1	134.5
	9.63	.941	28.2	140.3
	9.68	1.09	25.5	155.6
	9.50	2.47	26.3	149.7
	9.47	3.47	20.2	194.0
	9.56	4.50	21.9	180.1
	9.56	5.58	18.8	210.5
	9.56	6.10	19.4	203.6
	6.22	2.62	17.5	146.8
		3.77	18.9	136.4
		4.56	21.1	121.8
		5.78	18.7	137.2

(c) Number of orifices, 2; orifice spacing, 6 orifice diameters

Orifice diameter, in.	Airflow rate, lb/(sec)(sq ft)	Fuel-flow rate, lb/hr	Combustor static pressure, in. Hg abs	Velocity, ft/sec
0.0520	2.49	0.142	23.0	44.9
		.191	21.8	47.4
		.241	22.0	46.9
		.285	21.8	47.5
		.332	21.7	47.6
	2.51	.383	21.7	47.9
	2.49	.404	21.6	47.8
	3.49	.144	28.3	51.2
		.193	26.7	54.2
		.239	26.1	55.4

TABLE I. - Continued. COMBUSTION STABILITY DATA FOR HYDROGEN FUEL JET

(c) Continued. Number of orifices, 2; orifice spacing, 6 orifice diameters

Orifice diameter, in.	Airflow rate, lb/(sec)(sq ft)	Fuel-flow rate, lb/hr	Combustor static pressure, in. Hg abs	Velocity, ft/sec
0.0520	3.49	0.281	25.8	56.1
	3.50	.326	25.3	57.3
	3.49	.367	25.4	56.9
		.407	25.9	55.8
		.375	25.6	56.4
	3.49	.479	25.3	57.3
	3.51	.634	25.2	57.7
	3.52	.777	26.9	54.2
		.872	28.3	51.6
		.994	28.9	50.4
	2.32	.389	21.3	45.1
		.510	21.5	44.7
		.635	22.8	42.2
		.782	24.4	39.4
		.990	24.6	39.1
	2.49	.801	22.3	46.3
	2.47	1.04	24.3	42.2
	2.49	1.29	26.1	39.6
		1.55	25.4	40.7
		1.79	24.9	41.5
	3.50	.759	25.7	56.5
		1.01	26.4	55.0
		1.24	28.3	51.3
	3.51	1.51	28.8	50.5
	3.50	1.75	28.8	50.3
	3.50	2.00	29.2	49.6
	1.66	.705	19.0	36.3
		.938	20.4	33.8
		1.21	20.8	33.1
		1.43	20.4	33.8
	1.68	1.67	18.7	37.3
	1.68	2.00	18.1	38.5
	1.55	.427	17.5	36.7
		.525	19.2	33.6
		.642	20.1	32.0

TABLE I. - Concluded. COMBUSTION STABILITY DATA FOR HYDROGEN FUEL JET

(c) Concluded. Number of orifices, 2; orifice spacing, 6 orifice diameters

Orifice diameter, in.	Airflow rate, lb/(sec)(sq ft)	Fuel-flow rate, lb/hr	Combustor static pressure, in. Hg abs	Velocity, ft/sec
0.0520	1.55	0.784	19.9	32.3
		.902	20.2	31.8
		1.02	19.5	33.0
		.170	17.2	37.4
		.138	18.0	35.7
	1.55	.218	17.0	37.8
		.369	17.1	37.5
		.336	16.9	38.0
		.402	18.3	35.1
.0810	5.42	.410	27.8	80.4
	5.42	.610	23.7	94.3
	5.43	.787	22.3	100.4
		.914	22.8	98.4
		1.07	22.7	98.6
	3.53	.387	20.7	70.4
	3.53	.604	18.7	78.1
		.849	19.2	76.1
		1.08	19.1	76.2
	6.54	.582	30.4	88.7
	6.55	.826	27.1	99.7
	6.56	1.07	25.0	108.0
	6.60	.840	27.8	97.4
	6.57	1.33	25.8	105.0
	6.60	1.87	25.2	107.7
	6.57	2.17	24.1	112.2
	5.41	.828	24.6	90.5
	5.45	1.36	23.5	95.3
	5.47	1.97	22.6	99.4
	3.58	.808	19.5	75.6
	3.60	1.39	19.4	76.5
	3.60	1.97	20.8	71.3

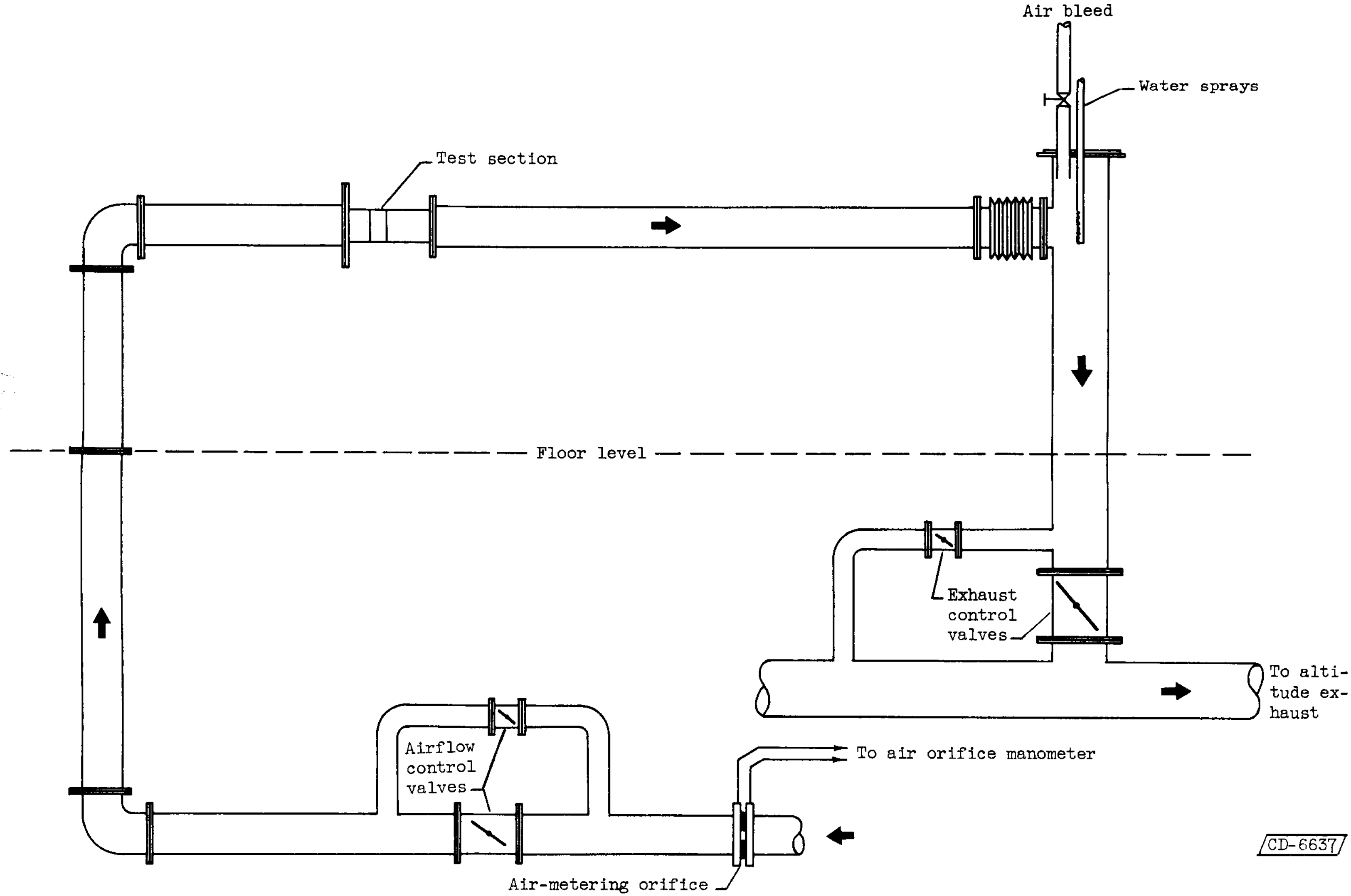


Figure 1. - Test facility.

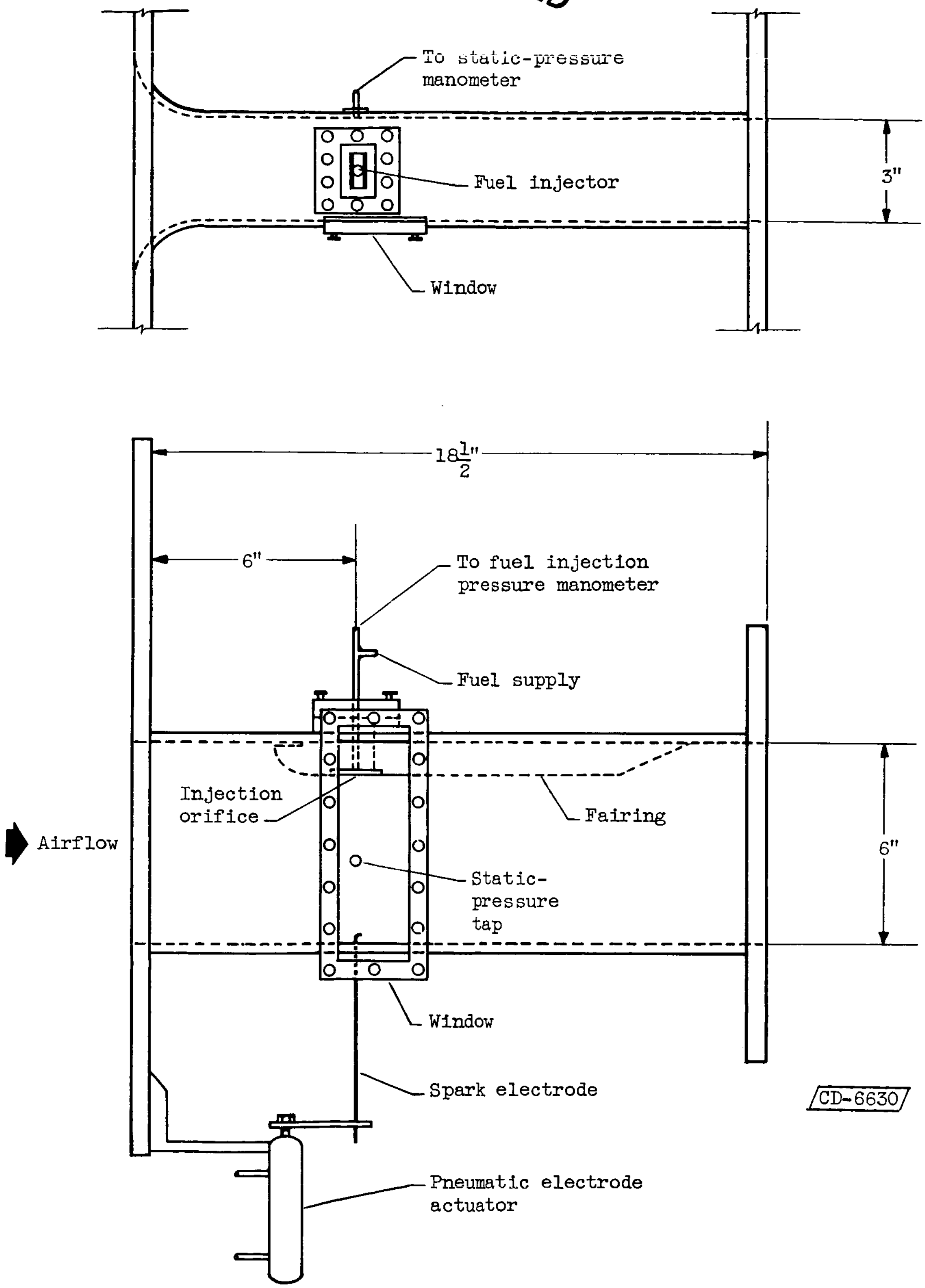
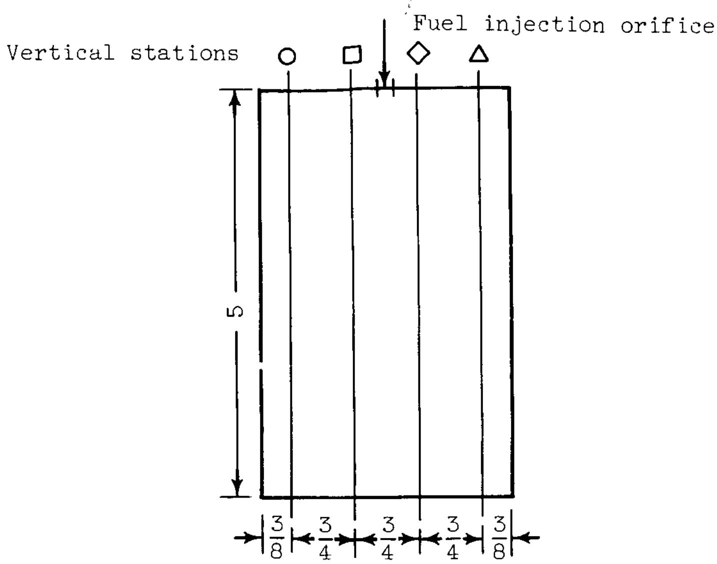
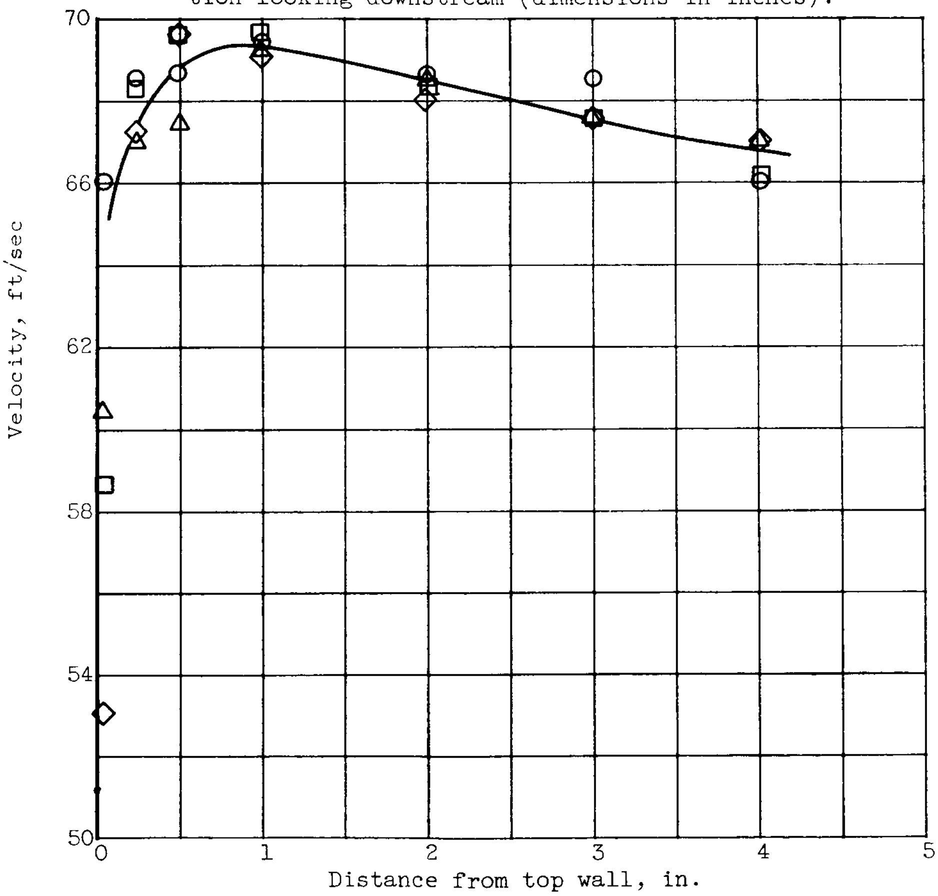


Figure 2. - Test section.



Combustor cross section at the point of fuel injection looking downstream (dimensions in inches).



(a) Combustor pressure, 14.0 inches of mercury absolute.

Figure 3. - Combustor inlet velocity profile.

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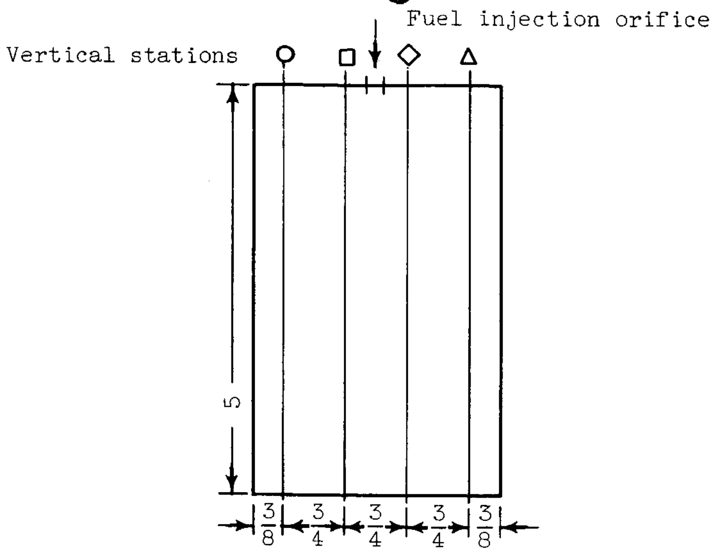
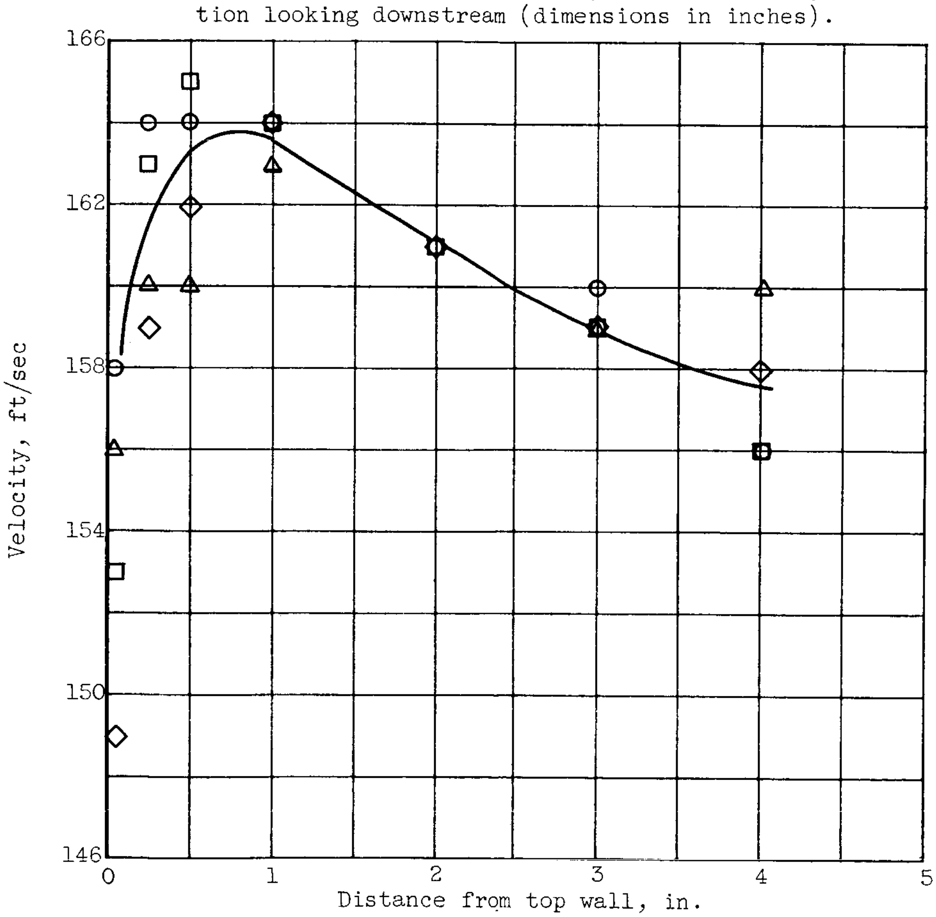


Combustor cross section at the point of fuel injection looking downstream (dimensions in inches).



(b) Combustor pressure, 26.8 inches of mercury absolute.

Figure 3. - Concluded. Combustor inlet velocity profile.

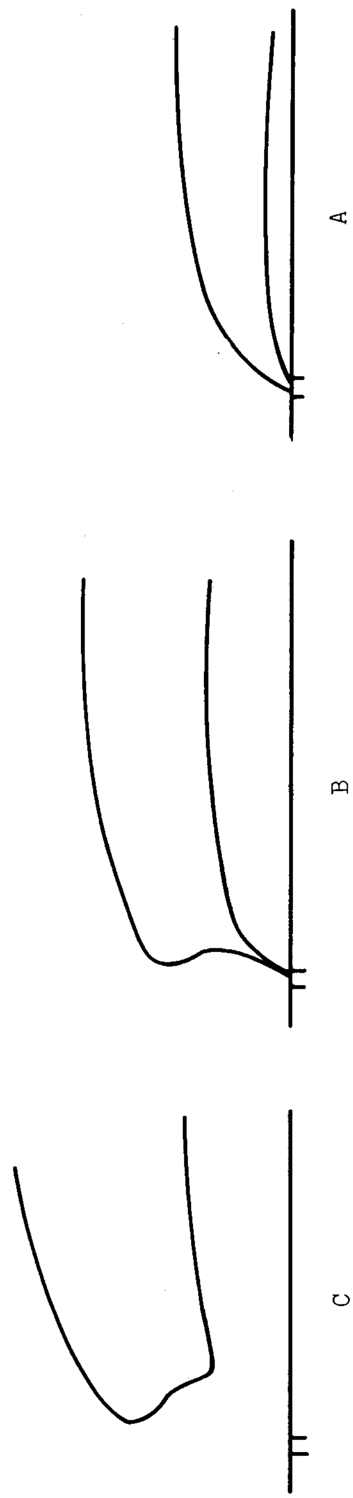


Figure 4. - Flame types.

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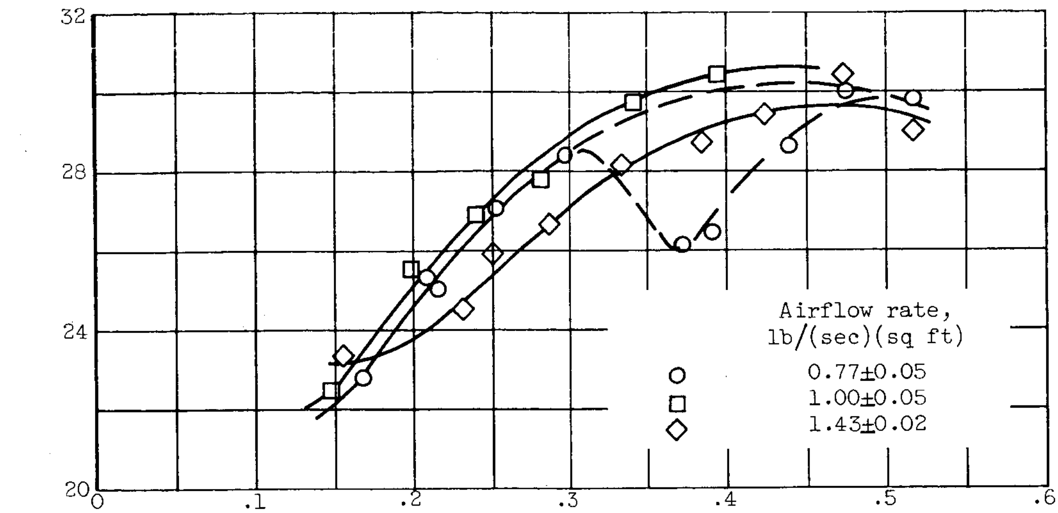
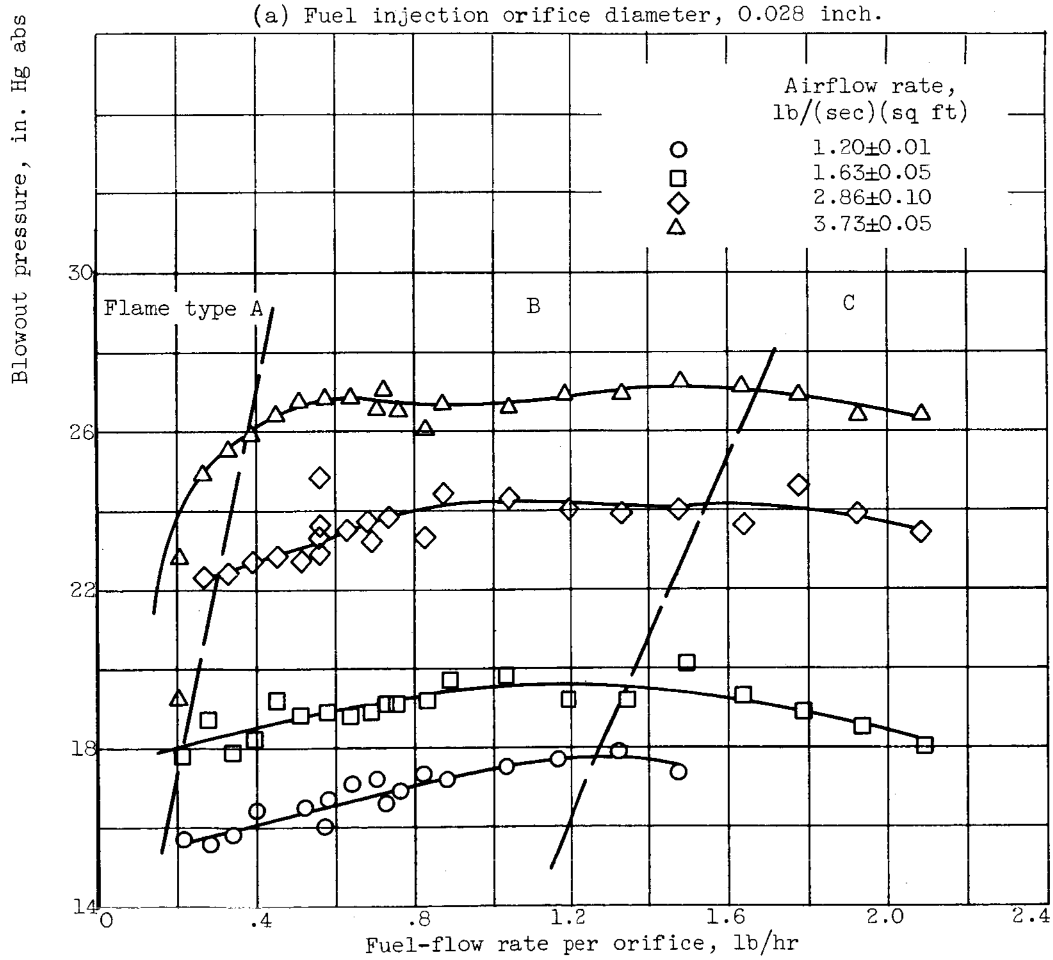
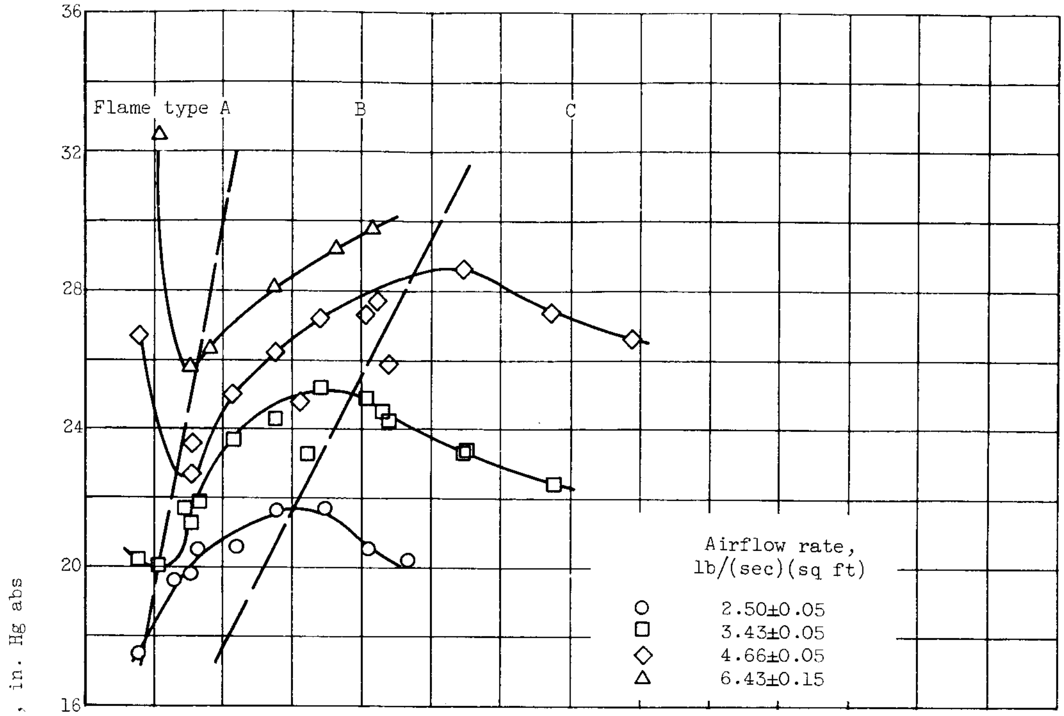


(a) Fuel injection orifice diameter, 0.028 inch.

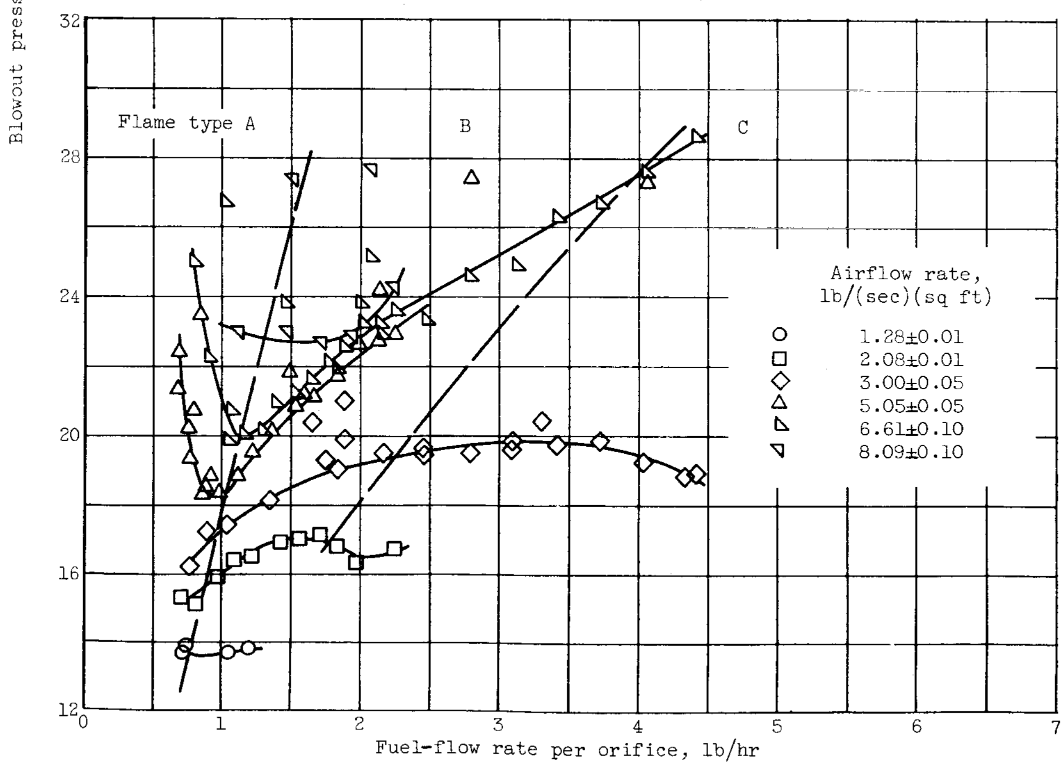


(b) Fuel injection orifice diameter, 0.052 inch.

Figure 5. - Variation of blowout pressure with fuel flow for single fuel injection orifices.



(c) Fuel injection orifice diameter; 0.081 inch.



(d) Fuel injection orifice diameter, 0.104 inch.

Figure 5. - Concluded. Variation of blowout pressure with fuel flow rate for single fuel injection orifices.

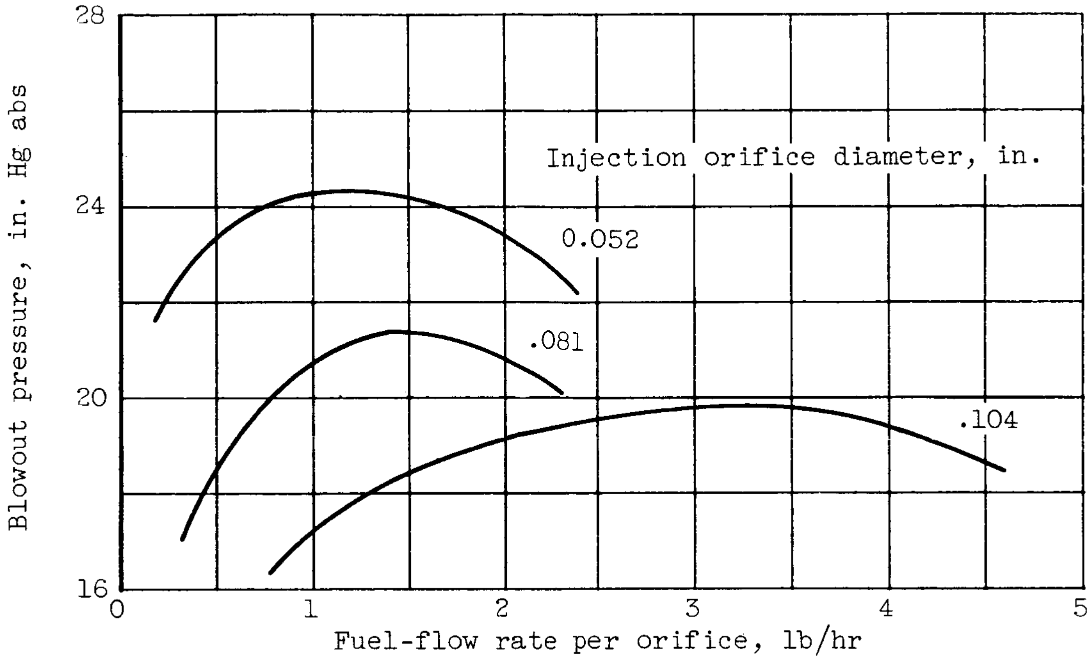


Figure 6. - Variation of blowout pressure with fuel-flow rate for different fuel injection orifice diameters. Airflow rate, 2.75±0.30 pounds per second per square foot.

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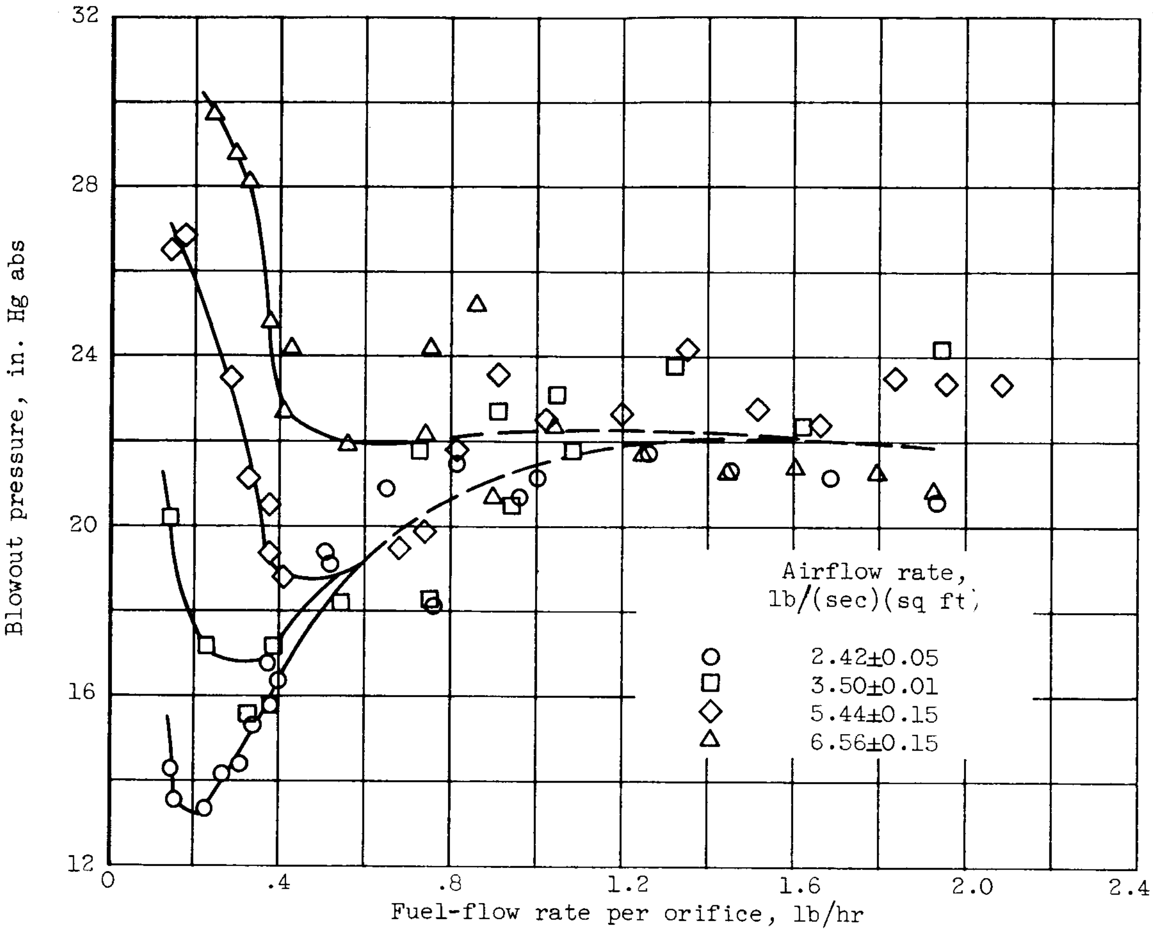
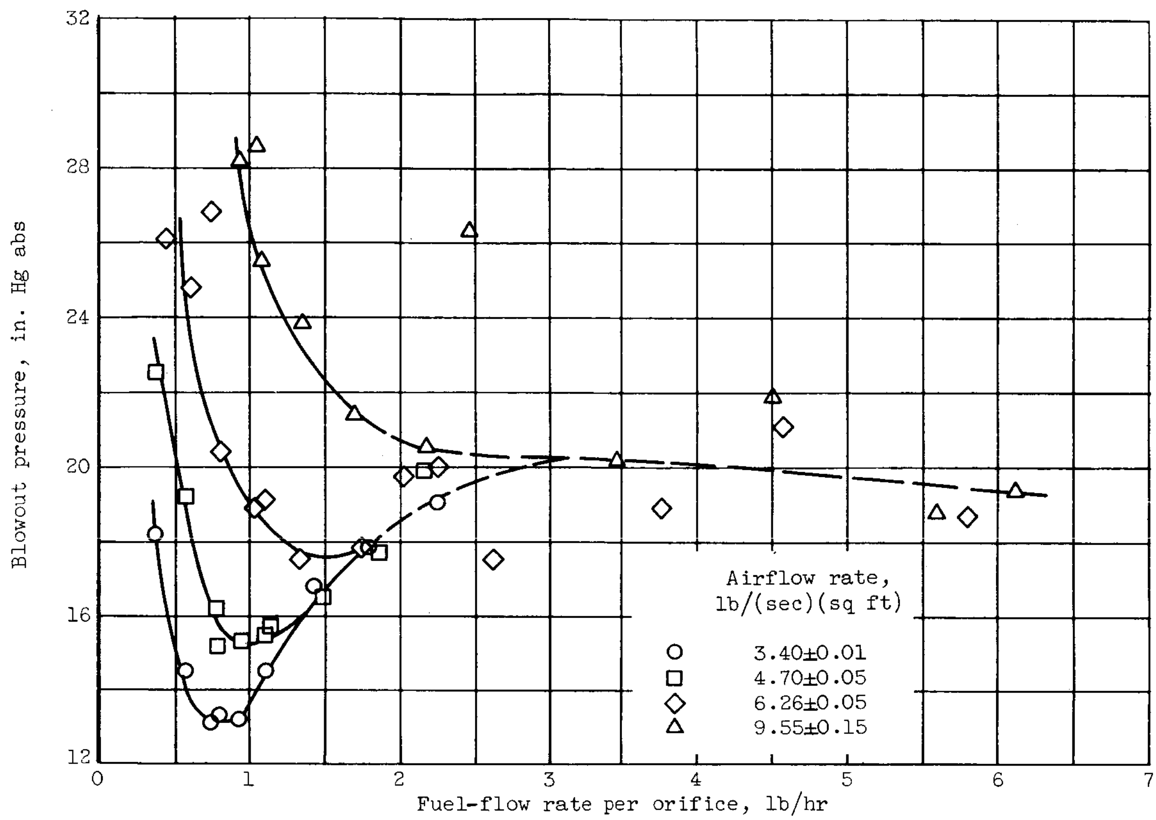


(a) Fuel injection orifice diameter, 0.052 inch.

Figure 7. - Variation of blowout pressure with fuel-flow rate for two fuel injection orifices spaced 3 orifice diameters apart.



(b) Fuel injection orifice diameter, 0.081 inch.

Figure 7. - Concluded. Variation of blowout pressure with fuel-flow rate for two fuel injection orifices spaced 3 orifice diameters apart.

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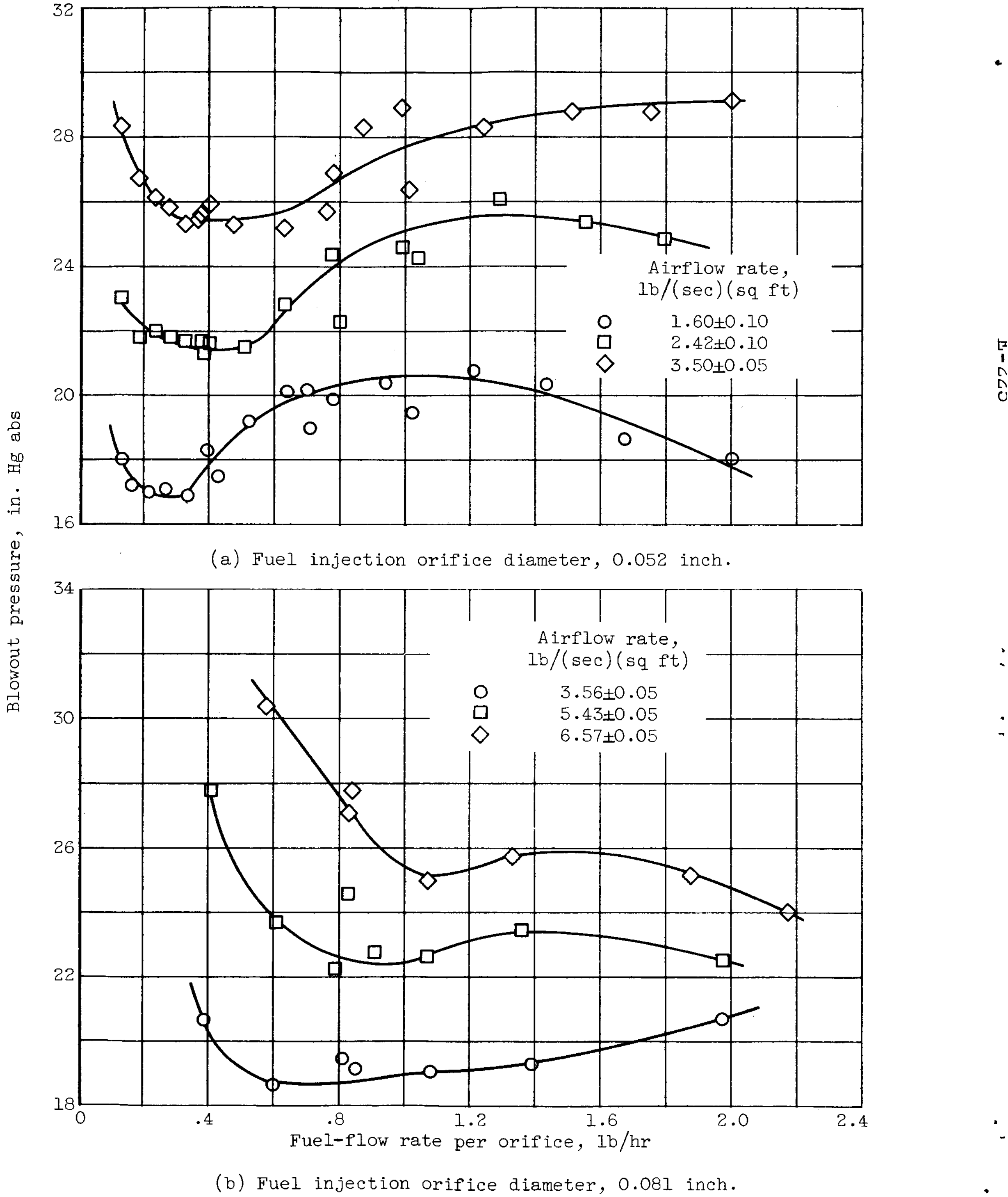

Figure 8. - Variation of blowout pressure with fuel-flow rate for two fuel injection orifices spaced 6 orifice diameters apart.

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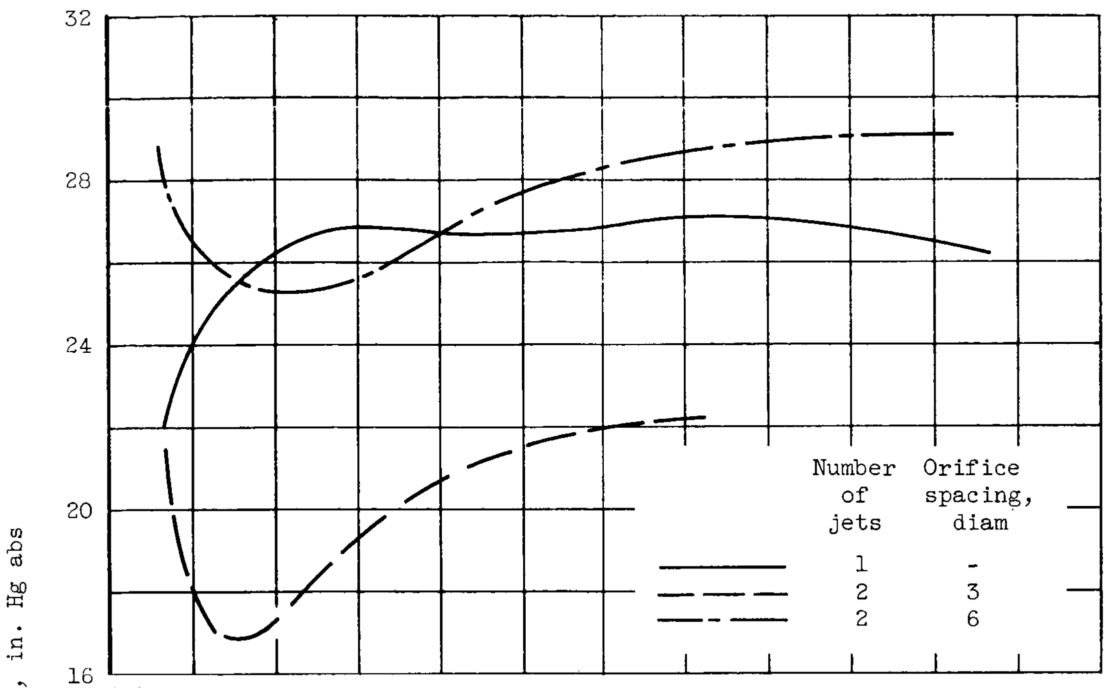
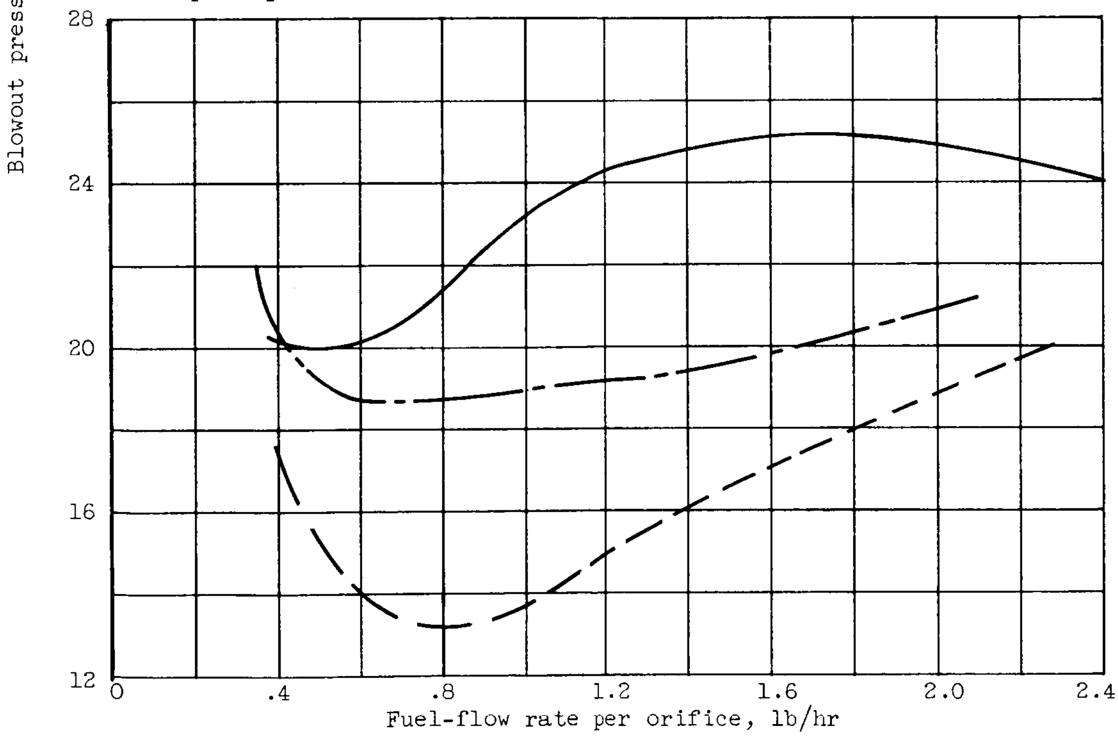
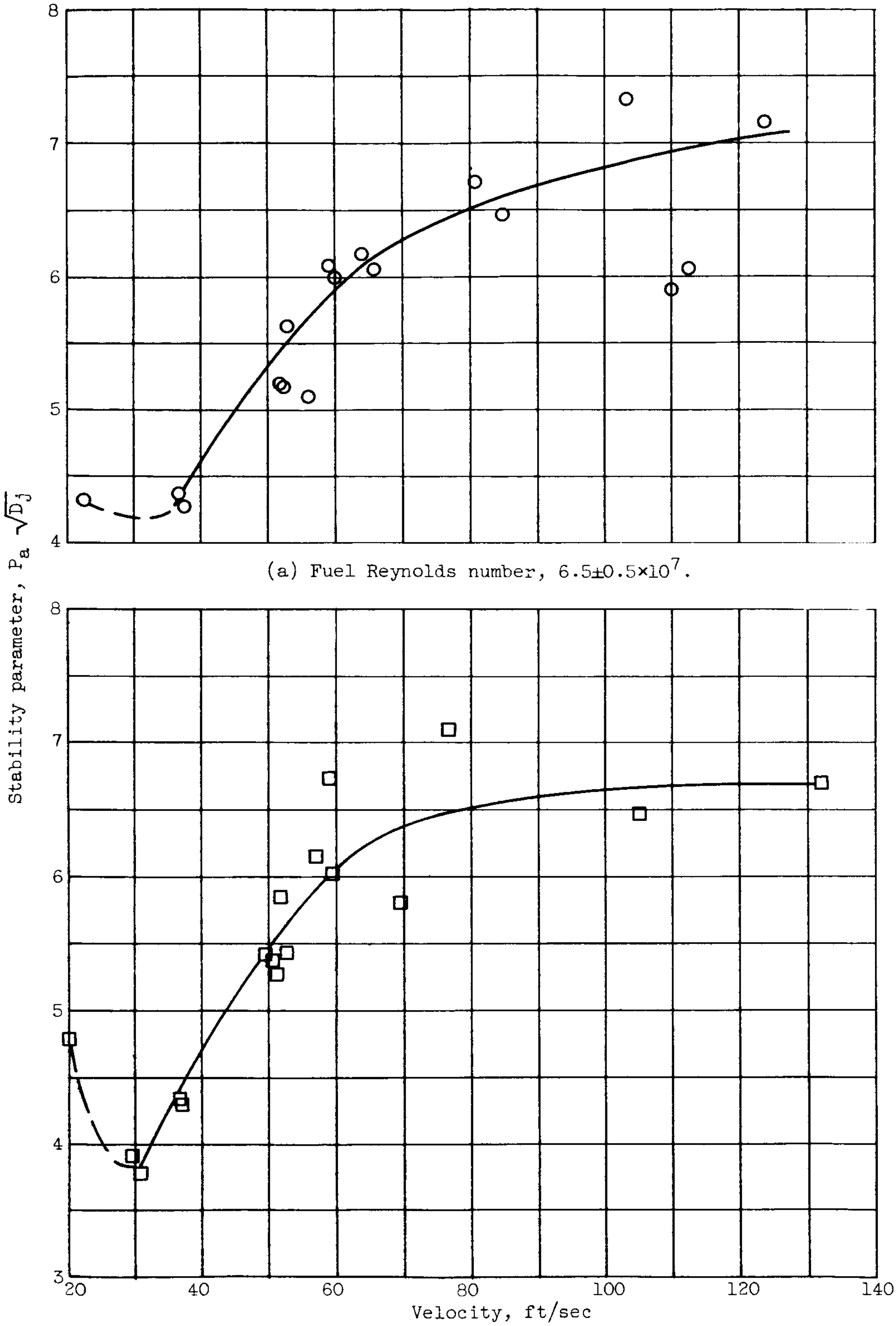


(a) Orifice diameter, 0.052 inch; airflow rate, 3.64±0.15 pounds per second per square foot.



(b) Orifice diameter, 0.081 inch; airflow rate, 3.51±0.10 pounds per second per square foot.

Figure 9. - Effect of injection orifice spacing on blowout for various orifices.



(a) Fuel Reynolds number, $6.5\pm0.5\times10^7$.

(b) Fuel Reynolds number, $9.5\pm0.5\times10^7$.

Figure 10. - Single jet correlation parameters.

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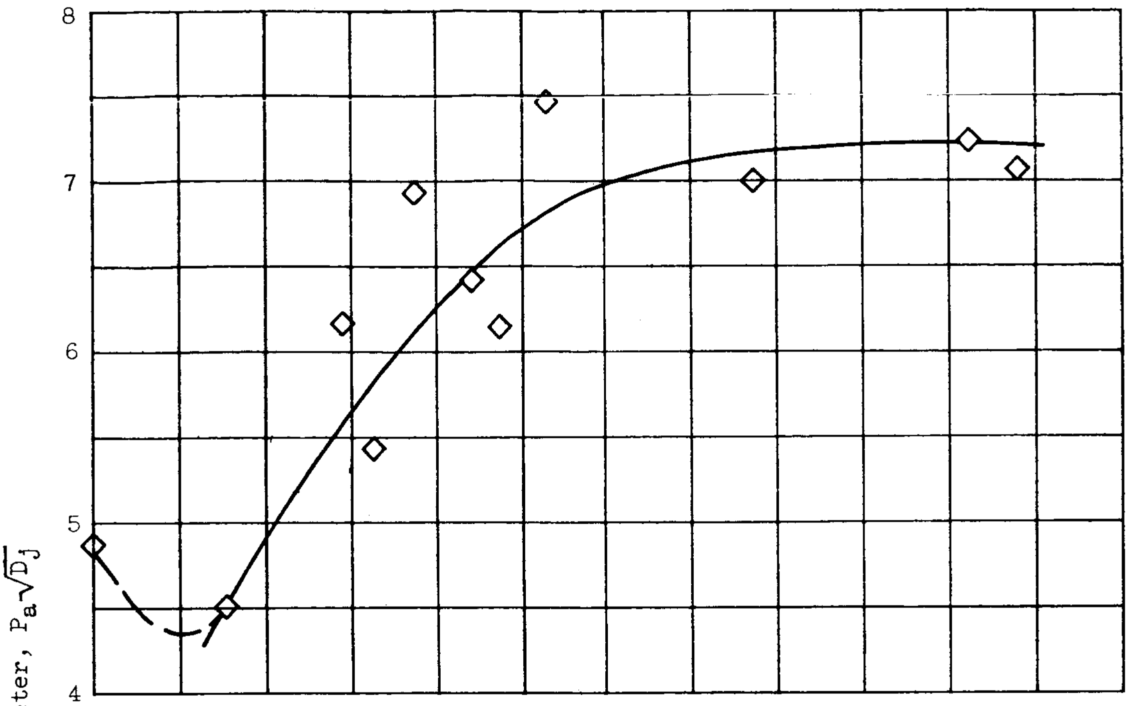
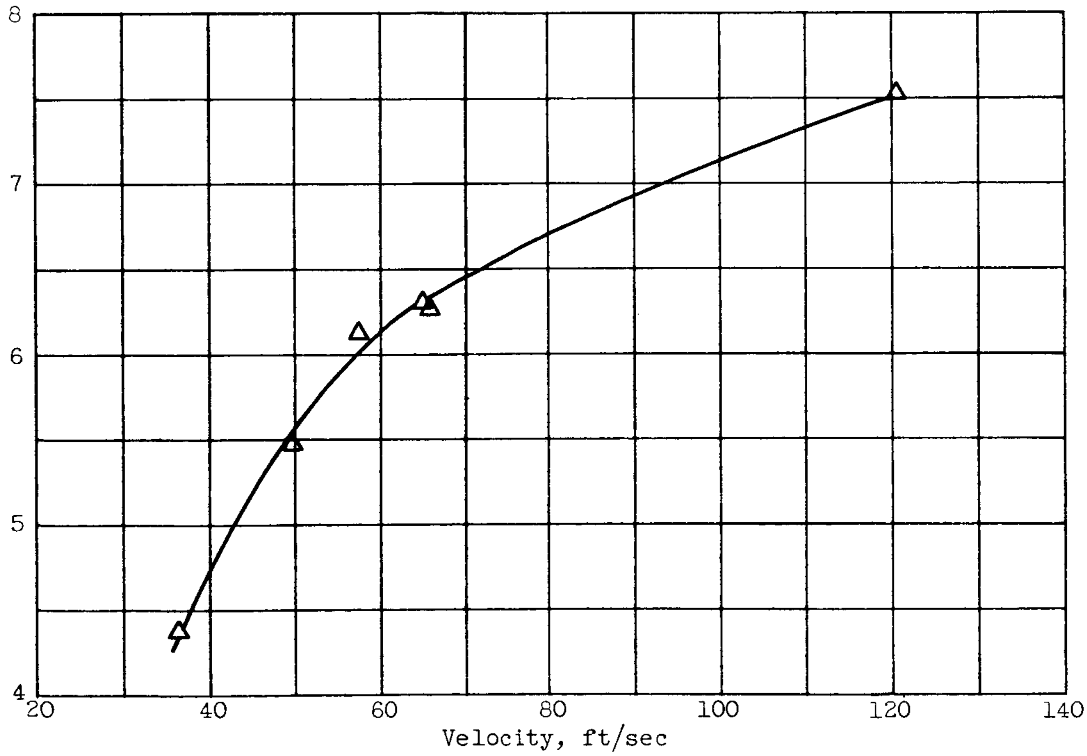


(c) Fuel Reynolds number, 12.5±0.5×10^7.



(d) Fuel Reynolds number, 16.5±0.5×10^7.

Figure 10. - Continued. Single jet correlation parameters.

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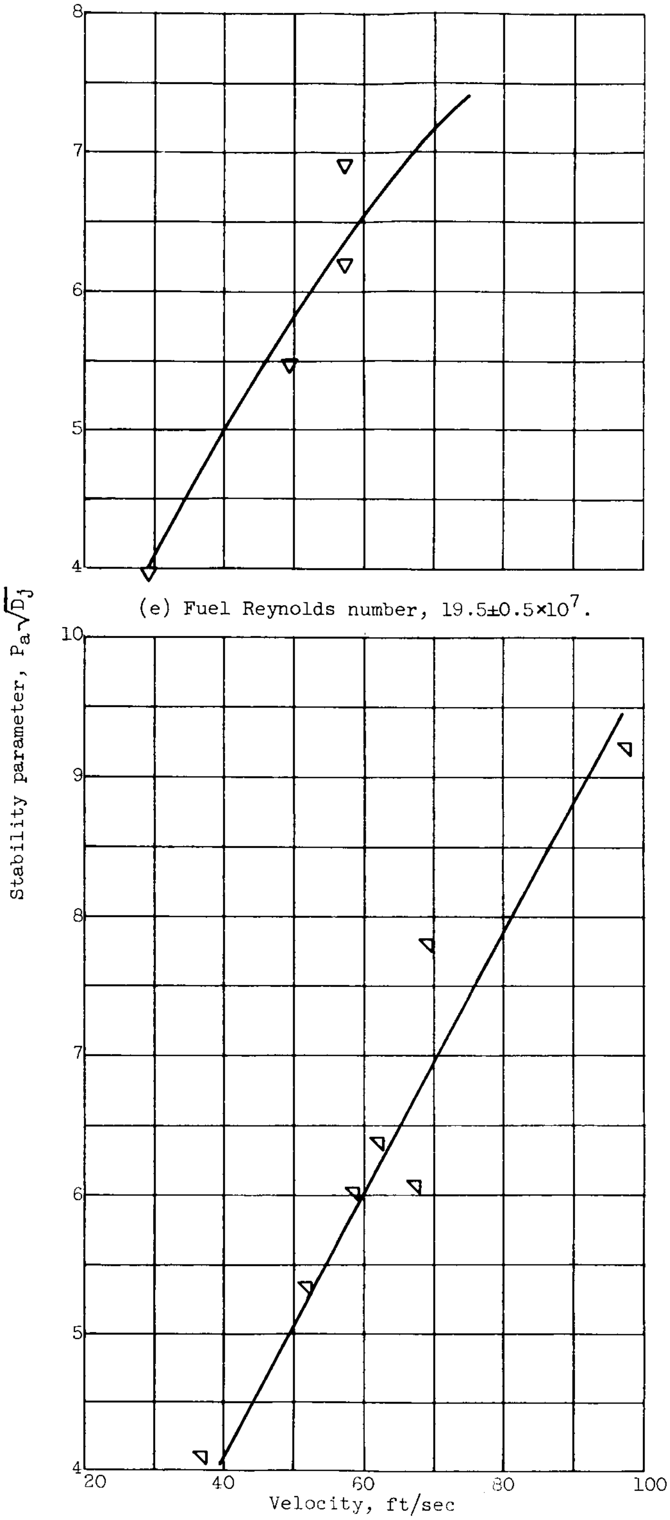

(e) Fuel Reynolds number, $19.5\pm0.5\times10^7$.

(f) Fuel Reynolds number, $29.0\pm1.0\times10^7$.

Figure 10. - Concluded. Single jet correlation parameters.